

Post-Red Supergiants

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Abstract. The yellow hypergiants are found in a stage between the massive Red Supergiants and the Wolf-Rayet stars. This review¹ addresses current issues concerning the evolution of massive stars, concentrating on the transitional post-Red Supergiant phase. Few yellow hypergiants are known and even fewer show direct evidence for having evolved off the Red Supergiant branch. Indeed, only two such rare objects with clear evidence for having gone through of a previous mass losing phase are known, IRC +10420 and HD 179821. We will review their properties, discuss recent results employing near-infrared interferometry, integral field spectroscopy and polarimetry. Finally, their real-time evolution is discussed.

1. Introduction

A large variety of evolved massive stars are present in the upper parts of the HR diagram. Amongst others, we find the hot, mass losing Wolf-Rayet (WR) stars (Crowther, 2007), the unstable Luminous Blue Variables (LBVs, Humphreys & Davidson 1994), the enigmatic B[e] supergiants (Zickgraf et al. 1986), the massive Red Supergiants (RSG, Massey et al. 2008) and in between these phases, the Yellow Hypergiants (YHGs, de Jager 1998). An HR diagram with LBVs, Yellow Hypergiants and Red Supergiants is shown in Figure 1.

A commonly cited evolutionary scenario linking most of these classes of object can be summarized as follows (e.g. Meynet & Maeder 2003). After a massive star with a mass of more than about $50 M_{\odot}$ moves off the main sequence it evolves straight to the WR phase via the B supergiant and LBV phases. In special circumstances it can then explode as a Supernova giving rise to a Gamma Ray Burst (e.g. Meynet & Maeder 2007). Lower mass stars with masses typically larger than $10 M_{\odot}$ evolve all the way from the blue to the red to become a Red Supergiant, during which phase they can lose half their mass via a strong, long lasting mass loss phase. When the star evolves off the RSG branch it can evolve via the YHG phase to the LBV phase to eventually become a WR star. It should be mentioned however that it is still not clear whether any

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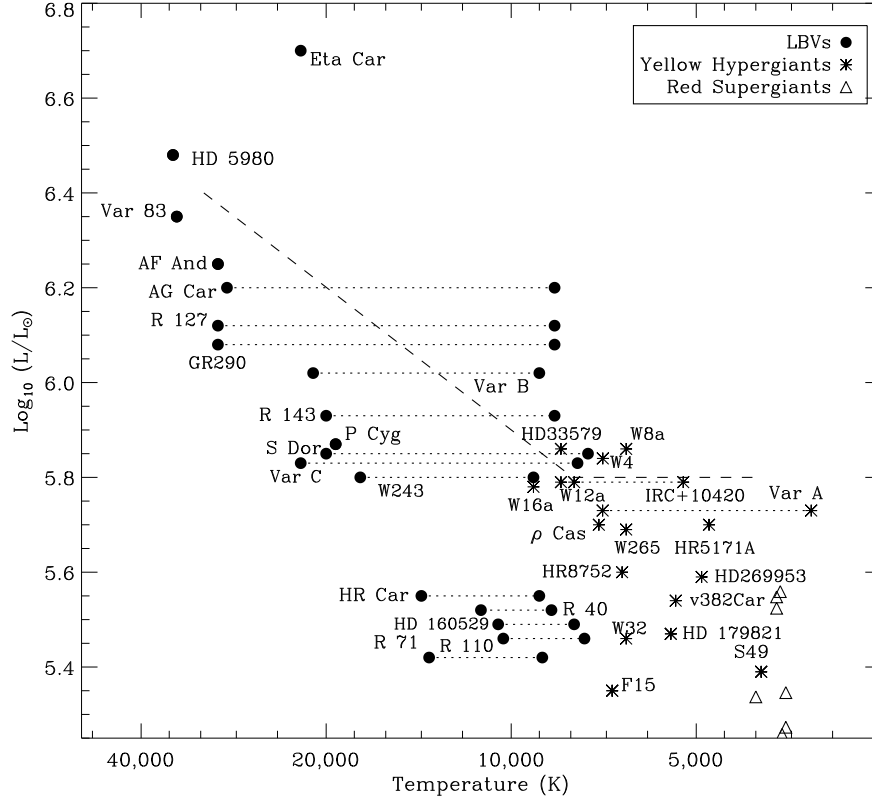


Figure 1. HR diagram displaying Luminous Blue variables (filled circles, taken from Smith et al. 2004), yellow hypergiants (asterisks) at their highest observed temperatures (de Jager 1998), and Red Supergiants (triangles) from Levesque & Massey (2005). Many Galactic YHG data are taken from de Jager (1998), HD 179821 is from Reddy & Hrivnak (1999). A large number of YHGs are now known from detailed studies of massive Galactic clusters. F15 is reported by Figer et al. (2006), Star 49 is presented by Davies et al. (2007a), and data for W4, W8a, W12a, W16a, W32 and W265 in Westerlund 1 are taken from Clark et al (2005). The dashed line denotes the Humphreys-Davidson limit.

LBVs have evolved off the RSG (e.g. Lamers et al. 2001). The situation proves even less settled for the B[e] supergiants, it is possible that they constitute a rapidly rotating sub-sample of the objects that evolve through the LBV phase.

In this paper, we focus on the evolutionary phase that immediately follows the Red Supergiant stage, the post-RSG phase. This term would of course apply to all objects, including the WR stars, that have visited the Red Supergiant branch at some point during their evolution. For the purposes of this paper, we will confine ourselves to the first stop in their journey from the RSG towards the blue. A quick glance at the HR diagram brings us then immediately to the Yellow Hypergiants. They are located on the red side of the LBVs and the apparent empty region in the HR diagram where the temperatures are between ~ 7000 and $10\,000$ K. As outlined in Figure 1, the LBVs vary in temperature between ~ 9000 K up to the S Dor instability strip, for which higher luminosities correspond to higher temperatures. The YHGs are located on the red side of this region, which has historically been referred to as the Yellow Void (e.g. de Jager and Nieuwenhuijzen 1997), and have not been observed to cross it bluewards. Given that the LBVs are found on the blue side of the Yellow Void and also do not seem to cross it, while the larger number of known LBVs and YHGs seem to fill in the “void” since the term was introduced, it could be argued that “Yellow Wall” is perhaps a more appropriate term.

Yellow hypergiant stars are not in a quiet phase of their evolution. Observationally they have been found to exhibit explosive events and to undergo multiple blue- to red movements and vice versa in the HR diagram. After the stars evolve from the RSG branch and reach temperatures around 7000 K, their envelopes become unstable and a large mass loss ensues (e.g. Stothers & Chin 2001). A large enough mass loss rate can give rise to an optically thick wind, or in other words, the central star is surrounded by a cool pseudo-photosphere. After the eruption has occurred, the motion of the star in the HR diagram reverses and the object now follows a redward loop returning to the RSG branch. After the wind clears, the star will be on a blueward loop again until it can “bounce” another time against the Yellow Void. This so-called “bouncing against the Yellow Void” has been observed in several instances. A compelling observation is presented by de Jager & Nieuwenhuijzen in 1997. They observed HR 8752 and found that it had undergone at least two such “bounces” in the preceding 30 years. In both cases, the bounce was associated with an episode of increased mass loss. Just before the mass loss event, the star had reached its maximum temperature, to decrease thereafter as expected for a newly formed thick pseudo-photosphere. The duration of these episodes is around 10 years for HR 8752. This is shorter than what has been observed for the object Var A in M33. Humphreys et al. (2006), observed a spectral type variation for this object from F to M and back to F again over a period of 45 years, and present evidence that the high mass loss and subsequent clearing of the pseudo-photosphere are responsible for the redward and blueward motions in much the same manner as explained above. Similar events, but at much smaller timescales have been observed for the famous object ρ Cas. Lobel et al. (2003) describe the latest outburst of the star during which its temperature decreased from 7000 K to less than 4000 K in a matter of a few hundred days, to increase back to almost 6000 K in roughly the same amount of time.

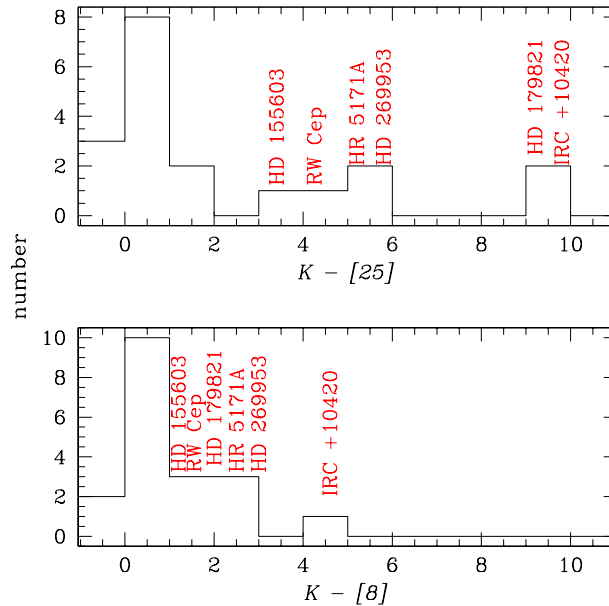


Figure 2. Infrared colours of the K-G-F-A super- and hypergiants listed in Table 2 of de Jager 1998. The upper panel shows the $K - [25]$ colour in magnitudes (17 objects), that of the lower panel the $K - [8]$ colour of 19 stars. See text for details.

Once a sufficient amount of mass has been ejected, and it is not yet clear how much, the stellar envelope can survive the instabilities and the star can evolve through the void to re-appear as an LBV. But this may not apply to all YHGs as speculated by Smith et al. (2004). Inspection of the HR diagram in Figure 1 reveals that there may be a gap in luminosity around $\log(L/L_{\odot})$ between 5.6..5.8 where there are apparently no LBV counterparts to the YHGs. Smith et al. propose that for stars within this luminosity range, their pseudo-photospheres will have even higher opacities due to the bi-stability mechanism (e.g. Vink et al. 1999). Subsequently they will not be visible as LBVs because the pseudo-photospheres effectively result in a YHG spectrum for a longer time. Instead, the objects that can cross the Yellow Void would only re-appear as the much hotter Ofpe/WN9 stars or B[e] stars.

2. Yellow Hypergiants as post-Red Supergiants

In part because of their definition, the Yellow Hypergiants occupy a rather limited area in the HR diagram. It may come as a surprise then that, apart from their status as evolved objects, their current evolutionary phases are varied and for many individual cases their precise status remains undetermined. Some objects have just left the Main Sequence and are on their first, redward, move towards the Red Supergiant Branch, some are on a blueward move, having just evolved off the RSG branch, while others have left the Red Supergiant Branch on a blueward track, but are returning on a redward loop. With the exception

of the stars that are crossing the Yellow Void on a redward track toward the RSG, all YHG's can be classified as post-Red Supergiants. However, it is not trivial to determine the evolutionary stage of a given YHG.

A key difference is that the post-Red Supergiants will have their surface enriched by CNO processed material, often also traced by their Na overabundance. Unfortunately, not many detailed abundance studies of YHG's have been performed. Klochkova et al. (1997) showed for IRC +10420 that the star is N-rich, indicating dredge-up of processed material. HD 179821 has been subject to 3 different abundance studies with differing conclusions with respect to its surface temperature. High temperatures, inconsistent with its G spectral type have been proposed (Zacs et al. 1996), as have lower temperatures (Reddy & Hrivnak 1999; Thévenin et al. 2000). The main issue appears to be methodological, namely how the FeI - FeII ionization balance can be properly reproduced, whilst at the same time resulting in a G star spectrum. It would seem that a hydrogen deficient photosphere could alleviate this problem, yet although hard to demonstrate, this would also hint at a post-RSG nature of the object. Evidence for processed, enhanced sodium is reported for ρ Cas (El Eid & Champagne 1995) and HR 5171A (Warren 1973), while HD 33579 and HR 8752 were found to have solar abundances (de Jager 1998 and Luck 1975 respectively). This has been taken as evidence that HD 33579 is on a redward evolution, crossing the Yellow Void for the first time. It should be stressed however that modern abundance determinations using improved model atmospheres and high resolution spectroscopy are lacking.

Another property of post-Red Supergiants is that they are surrounded by the remnants of the prodigious mass loss during the RSG phase itself. Despite searches for the presence of circumstellar material, not many YHG's have been found to exhibit evidence for a previous mass loss episode. Some hypergiants have been reported in the literature to have strong infrared excess emission due to circumstellar dust. With the new data from the Spitzer SAGE survey of the LMC (Meixner et al. 2006) that have recently become available it is timely to re-investigate the presence of infrared emission. We selected all K-G-F-A supergiants from Table 2 in de Jager's 1998 review, but excluded the well-known post-Asymptotic Giant Branch object AFGL 2688. We then searched in the catalogues of the SAGE Spitzer survey, 2MASS, the Gezari catalog, IRAS and MSX and plot their $K - [8]$ and $K - [25]$ colours as histograms in Fig. 2. For two objects $8\mu\text{m}$ fluxes were not available, and we used the IRAS $12\mu\text{m}$ flux instead. Also, we treated MSX $21\mu\text{m}$, Spitzer $24\mu\text{m}$ and IRAS $25\mu\text{m}$ fluxes equally. Of the 8 LMC supergiants listed in de Jager, 7 were detected by Spitzer.

The infrared bands probe the Rayleigh-Jeans tail of the stellar photospheres and for a naked star the colours would be close to zero. Clarke et al. (2005) showed that the $K - [8]$ and $K - [25]$ colours (with $[8]$ and $[25]$ denoting the magnitudes at the respective wavelengths) are a powerful diagnostic of excess emission due to circumstellar dust. Whereas Clarke et al. could identify excess objects with colours exceeding 0.4 magnitude, we have to be more cautious here. This is because the YHG's are variable and not all photometry is taken simultaneously, and the colours may be affected. This is illustrated by the fact that some stars would appear to have negative excesses, which is unphysical. Because of this, we prefer to remain conservative and only assume the presence

of excess for the objects with colours larger than 2 magnitudes. This results in 4 objects with infrared excess. HD 179821 and IRC +10420 stand out in terms of their huge infrared excesses, and mass loss rates in excess of $10^{-4} M_{\odot} \text{yr}^{-1}$ have been derived (Oudmaijer et al. 1996, Hrivnak et al. 1989). At longer wavelengths (not shown) the excesses are even more pronounced. HR 5171A does not have much cool dust, which would be indicative of a prolonged period of mass loss, while for the Magellanic Cloud object HD 269953, longer wavelength data beyond $25 \mu\text{m}$ are lacking.

The infrared data are not alone in demonstrating the small number of YHG with evidence for a previous period of mass loss. A very deep HST imaging survey by Schuster et al. (2006) confirms this. They observed the best-known YHGs, ρ Cas, HR 8752 and HR 5171A, but did not find any signs for extended emission. The only YHGs with evidence for extended shells are HD 179821 and IRC +10420 (e.g. Kastner & Weintraub 1995). It would appear that these two stars are the only ones with good observational evidence that they have evolved off the Red Supergiant phase recently and are thus key to study the post-Red Supergiant stage.

The lack of a detectable extended shell around the other objects either implies that they are evolving from the Main Sequence to the red for the first time, or that they have made one or more loops between the RSG and the Yellow Void. We can not exclude the possibility that the objects spend such a long time evolving slowly towards the blue that the dust shell has long since dispersed into the interstellar medium. This is not expected from evolutionary models that can predict an RSG to Wolf-Rayet phase evolution of a few hundred to a few thousand years (e.g. García-Segura et al. 1996), and many more objects should be found than currently known. In the remainder of this paper, we will continue with IRC +10420 and HD 179821.

3. The post-Red Supergiants IRC +10420 and HD 179821

As discussed above, the number of objects with evidence that they have evolved off the Red Supergiant branch is sparse. Arguably, only IRC +10420 is an undisputed post-Red Supergiant in the recent literature. Its high luminosity (both spectroscopically and inferred from its large distance), the large outflow velocity in CO (40 km s^{-1}) typical for a very luminous object and prodigious mass loss are as expected for an object in the post-Red Supergiant stage (e.g. Jones et al. 1993, Oudmaijer et al. 1996, Castro-Carrizo et al. 2007).

The literature has been more ambivalent about the nature of HD 179821, and we therefore take the opportunity to review the evidence that it is a massive evolved star. In most papers up to the nineties it was classed as a low to intermediate mass post-Asymptotic Giant Branch (post-AGB) object. The post-AGB phase of evolution is qualitatively almost identical to the post-RSG phase, as the star has evolved off the AGB where it lost a lot of mass and evolves towards higher temperatures. Many post-AGB stars display A-F-G supergiant spectra and are surrounded by circumstellar material (see e.g. the reviews by van Winckel, 2003, or Hrivnak, 2008). However, several pieces of evidence appear to indicate that HD 179821 is more likely to be a massive object, and thus in the post-RSG phase instead. To illustrate the high luminosity of both objects, we

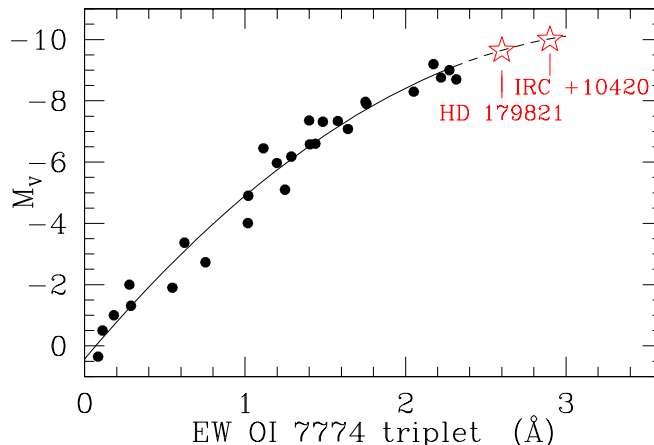


Figure 3. The M_V - $\lambda 7774$ Equivalent Width calibration. The data and fit are taken from Arellano Ferro et al. 2003. Both HD 179821 (data from Reddy & Hrivnak 1999) and IRC +10420 (data from Oudmaijer 1998) are off this published scale and very luminous, indicating their hypergiant nature.

show in Figure 3 the data and calibration of the OI $\lambda 7774$ absorption system. This triplet is a well known luminosity indicator and both IRC +10420 and HD 179821 have strong absorptions, indicative of a very low surface gravity. These two objects are even off the published scale and clearly stand out from this sample of very bright supergiants. A similar calibration was used by Clark et al. (2005), to determine the luminosity of the YHGs in Westerlund I. Indeed, the method was one of the primary methods to derive the distance to this cluster.

Jura et al. (2001) compared both objects' space (Local Standard of Rest, LSR) and expansion velocities of the mass outflows with those of local low mass AGB stars and found them to be separated from these lower mass objects both in space and expansion velocity. One can derive a distance to the objects using their v_{LSR} velocities and a model for the Galactic rotation curve. Jura et al. point out that both objects are at a distance of several kpc and note that based on the radial velocities alone, the luminosities are in excess of few hundred thousand times solar. The large CO outflow velocity of 30 km s^{-1} found for HD 179821 is less high than for IRC +10420, but very atypical for lower mass AGB and post-AGB stars. To achieve such high velocities a very luminous star is required to provide enough radiation pressure to accelerate the flow (see Habing et al. 1994).

Inspired by the rather unusual, but informative, manner Jura et al. (2001) plotted their data, we repeat the experiment using the large compilation of CO observations of evolved objects due to Loup et al. (1993). We selected all stars with observations of the CO 1-0 line and available expansion velocities and LSR velocities. In case of more than one entry, the first one in the list was taken. The resulting sample contains 332 objects and their expansion velocities are plotted against their space velocities in Fig. 4. Only the B-type binary HD 101584

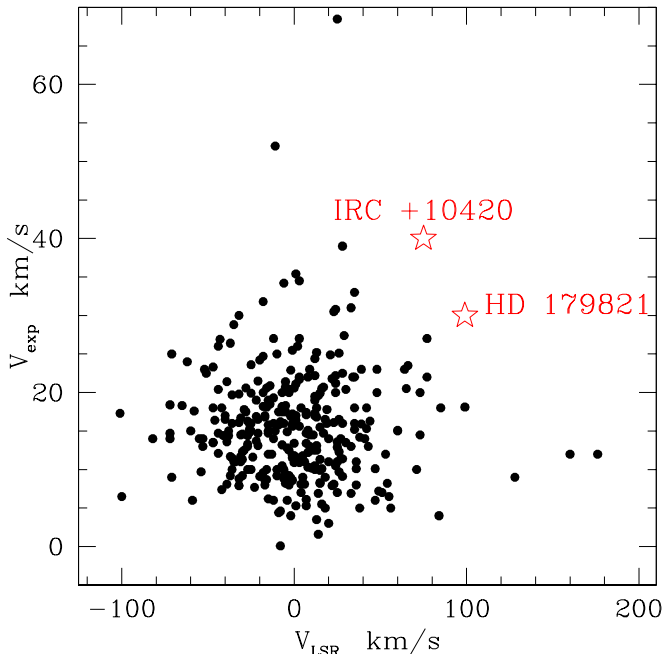


Figure 4. CO expansion velocities and LSR velocities of a large sample of evolved stars (Loup et al. 1993 - see text). Both post-Red Supergiants stand out.

(Bakker et al. 1996) is not plotted as its high outflow velocity of more than 100 km s^{-1} would make the graph less accessible.

We compute the average outflow velocity of this sample to be 16 km s^{-1} with a scatter of 10 km s^{-1} . This is the typical outflow velocity for low mass AGB stars and it can be seen that both HD 179821 and IRC +10420 stand out both in space velocity and expansion velocity. A number of objects have high outflow velocities but are normal in terms of their LSR motion and vice versa. To check whether there are objects with properties similar to post-RSG objects in the sample, we studied these objects in a bit more detail. We find 26 objects with expansion velocities larger than 29 km s^{-1} (arbitrarily chosen to be somewhat less than HD 179821's). Precisely half of these are carbon-rich AGB stars, 5 are classified Planetary Nebulae, 4 are oxygen-rich, including the well-known M supergiants VY CMa and VX Sgr. The other two are the M stars V341 Car and OH231.8+4.2. The remaining 4 objects include the aforementioned HD 101584 and the well-known Frosty Leo nebula (a K7III AGB/post-AGB object with strong bi-polar jets, Castro-Carrizo et al. 2005). The high CO velocities for these two objects reflect the presence of high velocity bi-polar outflows, but do not necessarily represent the outflow velocity of the preceding mass losing phase. The final two stars are HD 179821 and IRC +10420.

Since the objects in Loup's sample with known chemistry are equally divided between carbon-rich and oxygen-rich objects, the preponderance of C-rich AGB stars in the high velocity sub-sample may be a real effect. As the stellar parameters of O- and C-rich AGB objects are roughly the same, the reason for the higher velocities in some objects is most likely to be found in the dust absorption properties of carbon-rich dust. A higher absorption efficiency gives

stronger radiative driving and could result in some objects with large outflow velocities. A few objects with low outflow velocities, have large LSR velocities. Although this is known (Feast et al. 2006), its origin is unclear. It can be argued that the velocity dispersion of an evolved, low mass population is large, and that some outliers can therefore always be expected from a statistical point of view. It is also possible that some of these objects are run-away stars after a Supernova explosion from their companion. As with Jura et al.’s 2001 graph, both post-Red Supergiants stand out in this sample, and there is no indication of more such objects in Loup’s catalog, although it will be interesting to see whether similar objects have been observed since.

The above two, very different, examples of investigating objects illustrate the special place that both IRC +10420 and HD 179821 occupy in different samples of object, and we conclude that HD 179821 is also a massive star that has evolved off the post-Red Supergiant phase.

3.1. Geometry of the circumstellar material

Up til now, it is not clear which mechanism is responsible for the shaping of the ring nebulae around WR stars, the aspherical Supernovae ejecta and even the beamed Gamma Ray Bursts. A key question is whether the shaping of the ejecta takes place during the Red Supergiant phase, or thereafter (e.g. Dwarkadas & Owocki 2002).

This is an area where the study of post-Red Supergiants can be critical. The extended shells around both IRC +10420 and HD 179821 show considerable structure, but at the largest scales they are both, to all intents and purposes, fairly spherically symmetric. This could be seen already in the data of Kastner & Weintraub (1995). The deep images of Humphreys et al. (1997) show an almost annular appearance for IRC +10420. Similarly, the HST data of Ueta et al. (2000) show a predominately round shell for HD 179821. High resolution CO data by Castro-Corrido et al. (2007) confirm that the shells ejected during the Red Supergiant phase are largely spherical.

There has been an interesting debate on the geometry of the $H\alpha$ line emitting region around IRC +10420. This line originates much closer to the star than the dust and CO emission, and therefore traces recent events. On the one hand, indirect evidence seemed to suggest it deviates from spherical symmetry (e.g. Jones et al. 1993; Oudmaijer et al. 1994), on the other hand, spherical symmetry has been proposed (Humphreys et al. 2002). The latter authors used a novel and innovative method to establish this. By taking spectra of the reflection nebulosity around IRC +10420, they could effectively observe the $H\alpha$ emission line from different directions. This is because the dust particles located along the rotation axis of the object can see a “pole-on” view of the $H\alpha$ line emitting region, and scatter those photons to the observer, the particles perpendicular to this axis would do the same, but see, and scatter, an “edge-on” perspective.

Humphreys et al. (2002) employed the STIS instrument on board the HST and observed IRC +10420 at two different slit positions. They found the observed, reflected, $H\alpha$ profiles - taken as far as several arcsec from the central star - to be similar and concluded that the line forming region is spherical. An, unavoidable, limitation of their observational setup is that only few viewing an-

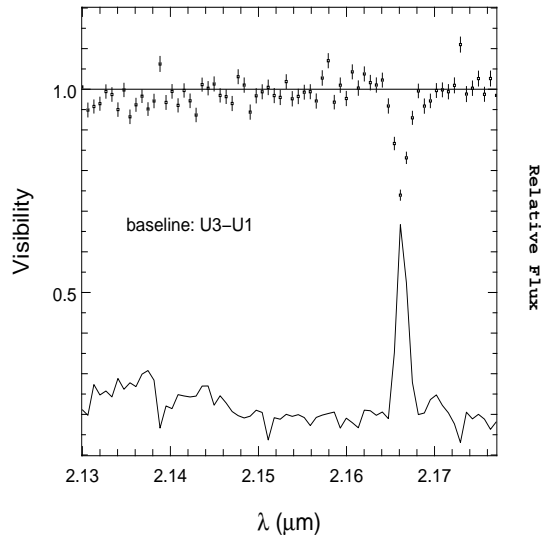


Figure 5. AMBER/VLTI data of IRC +10420. The spectrum is centered at $\text{Br}\gamma$ and has a resolution of 1200. The visibility resulting from the longest baseline UT1-UT3 with a projected baseline of 69 m for the observational set-up. The size of the line-emitting region is found to be of order a few milli-arcseconds. From de Wit et al. 2008

gles are available. Below we present data that concern a full 360° view of the $\text{H}\alpha$ emission. But let us first double check whether the ionized region is indeed point-like in relation to the dust. This is a tacit, but crucial, assumption when using the scattering method.

We obtained AMBER/VLTI interferometry of IRC +10420. This near-infrared spectrograph uses the light combined from the 8.2 m ESO Unit Telescopes UT1, UT2 and UT3 (e.g. Petrov et al. 2007). The data were centered on the hydrogen recombination $\text{Br}\gamma$ emission line. As the field of view of the instrument is 66 milli-arcseconds, all the dusty emission that would be visible at the K band is resolved out (see e.g. Blöcker et al.’s 1999 visibility calculations), and only the star and the $\text{Br}\gamma$ radiation - if originating from a small region - is present. Our data at the longest baseline are shown in Fig. 5 (from de Wit et al. 2008). The star is unresolved at these wavelengths, the $\text{Br}\gamma$ line has a smaller visibility and is clearly and unambiguously resolved. Preliminary model fits to the data indicate that the diameter of the line emitting region is 3.3 milli-arcseconds. This finding confirms that the reflection method can be used, as the ionized region is located up to a factor thousand closer to the star than the reflecting dust.

If the $\text{Br}\gamma$ emission is optically thin, then the observations do not allow one to make any inferences about the shape of the line forming region. This is because the baselines only sample a small range of position angles on the sky (between 10° and 30°). However, for optically thick line emission, we can do this using simple arguments. The observed diameter, obtained along one po-

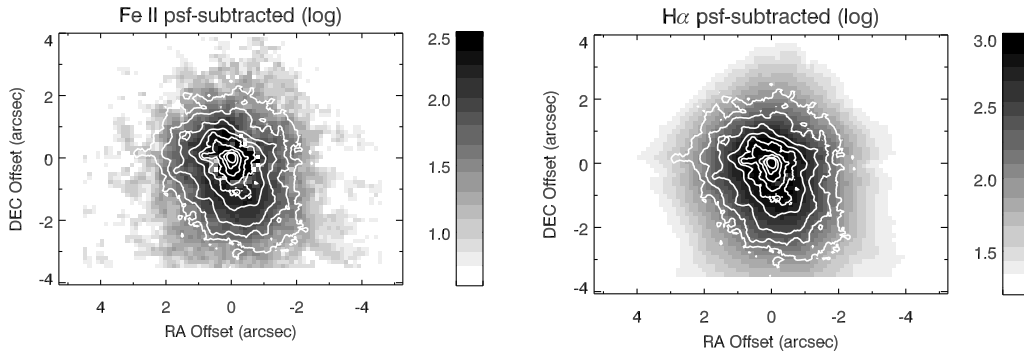


Figure 6. Adaptive optics assisted IFU data of IRC +10420. The left panel shows a continuum subtracted image of the $H\alpha$ emission line. The right hand panel shows the $FeII\lambda$ 6516 line. Both lines follow the reflection nebula, outlined by the white contours, closely.

sition angle, implies that the projected surface area is about ten times larger than that of the star if the line forming region is circular. If the $Br\gamma$ emission is optically thick, de Wit et al. (2008) then demonstrate that the $Br\gamma$ emission line should be an order of magnitude stronger than is actually observed. This discrepancy can be explained if the geometry is not circular in projection, but elongated. In this situation, the projected area of the ionized region can be smaller and, therefore, a weaker emission line is observed. Future VLTI data are planned to improve the uv coverage so that we can directly probe the geometry of the circumstellar material. The future is exciting, with imaging interferometers operating in the optical and near-infrared such as the Magdalena Ridge Observatory Interferometer becoming in operation soon (Creech-Eakman, 2008), we can begin to properly parametrize the winds of evolved stars.

Returning to the reflected spectrum of the central star, we used adaptive optics assisted integral field spectroscopy with the 4.2m William Herschel Telescope (Davies et al. 2007b). The integral field set-up covers the entire nebula and allows us to trace the reflected line emission at more than only a handful of slit-positions. The spectra, with a spatial resolution of half an arcsecond covered the $H\alpha$ line and a strong $FeII$ emission line at 6516\AA . The continuum subtracted images of both these lines are shown in Fig. 6, overplotted is a contour plot of a (higher resolution) blue HST image tracing the scattered light. The emission lines follow the reflection nebula very closely and are an independent confirmation that the line emission is reflected rather than formed in situ. The data do not have the spectral resolution to study the emission line profiles in detail. Instead, the $H\alpha$ equivalent width is shown in Fig. 7. The line EW is not constant, but exhibits a strong variation over the nebulosity. The EW changes from around -60 \AA in the south-west to less than -50 \AA in the north-east. As the equivalent width measures the line strength compared to the stellar continuum (which is reflected equally in all points), the change in EW indicates that the line emitting region is *not* isotropic. This result, which is in apparent contra-

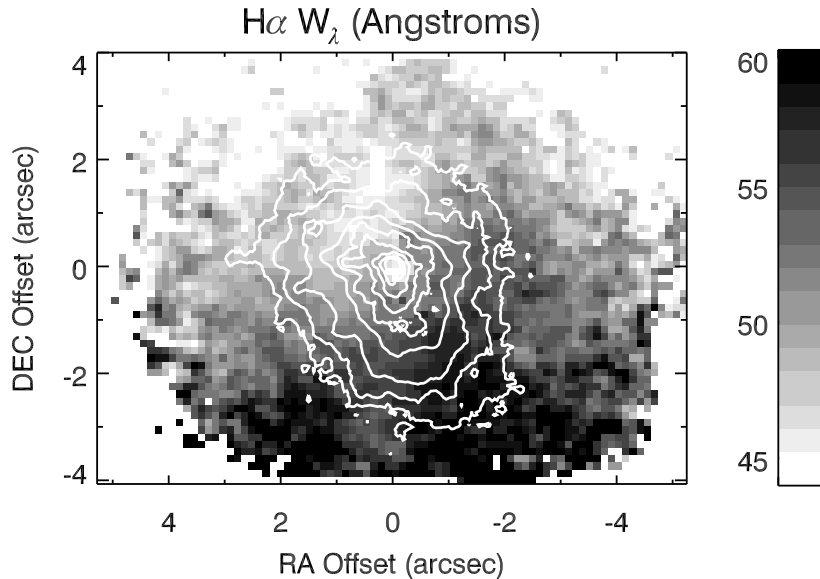


Figure 7. The $H\alpha$ emission Equivalent Width measured over the reflection nebula. The variations indicate that the line-forming region is not isotropic.

diction with the results from Humphreys et al. (2002), who did not find such strong variations, can be readily explained. The slit positions Humphreys et al. employed turned out to probe a region where the change in EW is minimal.

The axi-symmetry in the $H\alpha$ equivalent width is oriented perpendicularly to the long axis of the nebula. Although the current result is strong evidence for an inhomogeneous $H\alpha$ emitting region, the mechanism responsible for it can not be identified based on these data. It will be interesting to follow-up this study at higher spectral resolution to investigate the nature of the different line profiles.

3.2. Evolution of the objects

Let us now turn to the evolution of both HD 179821 and IRC +10420. Patel et al. (2008) collected optical and near-infrared photometric data from the literature for both objects and the results are presented in Fig. 8. The sources for the photometry are listed by Patel et al. Only a few near-infrared data points have been reported for HD 179821 over the last 20 years, which is particularly striking as it is such a bright object. The properties of both stars in the near-infrared photometry are very similar, the J and K band magnitudes have become fainter over the past 40 and 20 years respectively. The V band photometry shows modest changes and is correlated with the near-infrared variability.

From model fits to the Spectral Energy Distributions, the J band is known to trace the stellar photosphere (see Oudmaijer et al. 1996 and Hrivnak et al. 1989), so the changes do reflect variability of the star itself. Overall, the photometric changes can be explained by a gradual increase in temperature of the objects. In the case of IRC +10420 this has been confirmed spectroscopically.

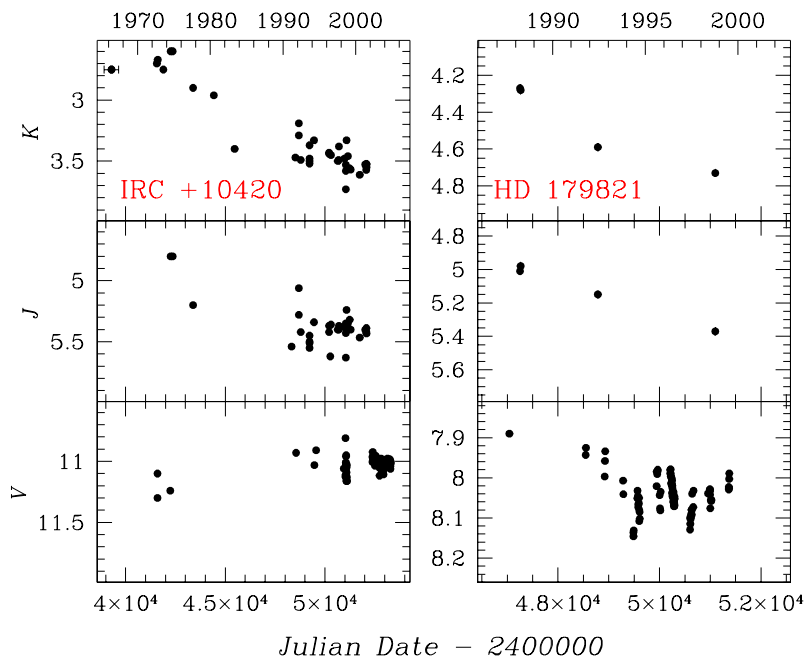


Figure 8. Photometric history for both objects over the past decades. Especially the changes in the J band, tracing the stellar photosphere, indicate the temperature increase of the stars. Data taken from Patel et al. (2008).

Klochkova et al. (1997), in a study based on the data of Oudmaijer (1998), find that the star must have a temperature consistent with an A supergiant - as opposed to F8I derived from a spectrum 20 years earlier. The J and V band photometry have reached a steady state over the past 10 years and although an increase in temperature is not excluded by these data, it may well be that IRC +10420 has now hit the “Yellow Void” and will not evolve further to the blue. It is tempting to speculate that a large outburst and a subsequent move to the red as observed for ρ Cas, HR 8752 and Var A is imminent. The change in photometry for HD 179821 is a new result and needs confirmation with spectroscopy. Although several spectroscopic studies of HD 179821 have been published, as mentioned earlier, the abundance studies unfortunately disagree on the temperature of the star, this is due to different methodology rather than an evolutionary effect (see for example the discussion by Thévenin et al. 2000).

To summarize, both stars appear to be evolving in real time. Whereas IRC +10420 may have slowed down its evolution, HD 179821 is still going strong and is evolving to the blue. As an aside, the added value of the near-infrared J band proves to be a very useful diagnostic to trace photospheric changes. The prospect of AAVSO observers being able to obtain near-infrared photometry (Templeton, 2008) is very exciting indeed.

Patel et al. (2008) also collected polarization data from the literature. They restricted themselves to R band data in order to compare with their $H\alpha$ spec-

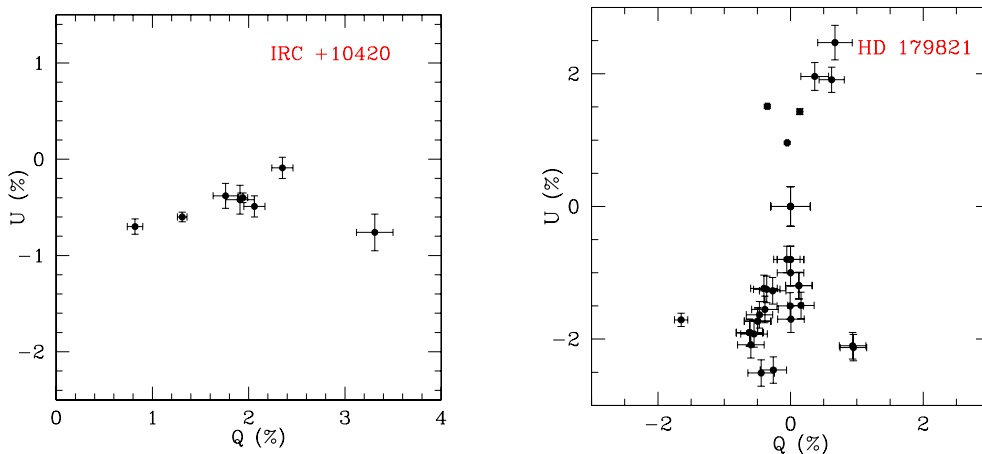


Figure 9. The Polarization Stokes QU parameters measured in the R band of both stars taken over several decades (data from Patel et al. 2008).

tropolarimetric data. The results represented in the Stokes QU vectors² are shown in Fig. 9. The point by Trammell et al. (1994) at $(Q, U) = (1.7\%, -3.2\%)$ falls outside the plot boundaries. As with the photometry, the polarization data span several decades, and it is clear that both objects are highly variable in polarization. Broadly speaking, the polarization smoothly changes over time by several per cent, but the causes are different for both objects. The polarization observed towards evolved stars can normally be interpreted as due to the scattering of photospheric radiation by either circumstellar free electrons or dust particles. The material needs to be distributed aspherically however. In the case of a spherically symmetric shell, all polarization vectors cancel out and no net polarization would be observed. For other geometries, such as a disk, not all vectors cancel out and a clear polarization signature is observed. If the scattering optical depth changes, due to variations in mass loss or ionization for example, the net observed polarization changes as well. This is precisely what we see for IRC +10420, the polarization increase occurs in tandem with the increase in $H\alpha$ equivalent width (Patel et al. 2008) and can be traced back to a more heavily ionized, asymmetric ionized shell. For HD 179821, the situation is less clearcut. Based on the $H\alpha$ absorption, we can infer that the star has virtually no ionized gas around it, and certainly not enough to induce a polarization of several per cent. However as outlined above, the dust shell is spherical as well, and it is very hard to reconcile the large polarization, or its variability, with the classic picture of polarization due to an aspherical circumstellar matter distribution. Instead, Patel et al. propose that it is the star itself which is an-isotropic. This scenario has been suggested, and is well accepted, to explain the polarization properties of cool stars. For example, Betelgeuse is observed to have large, bright convection cells on the stellar surface. These illuminate the circumstellar material an-isotropically and give rise to net polarization (Hayes 1984, see also Ignace & Henson 2008). HD 179821 is warmer than Betelgeuse,

²The polarization $P = \sqrt{Q^2 + U^2}$

but can be expected to have bright spots on the star as well. Any variability can be due to the combined effect of its non-radial pulsations (Le Coroller et al. 2003) and its stellar evolution described above.

4. Final Remarks

The Yellow Hypergiants are in a short-lived phase between the Red Supergiant stage and the end phases of massive star evolution. Yet, although their numbers are small, their properties are varied. The stars have been found to have very large mass loss rates at high outflow velocities, move along various loops in the HR diagram, bounce off a Yellow Void which they seem forbidden to cross, exhibit eruptive moments of mass loss and generally are amongst the visually brightest objects in any stellar population. They are key objects that link the comparatively well understood Red Supergiants and the Wolf-Rayet stars, not only in terms of evolutionary connections, but also with regards to the development of the circumstellar structures.

Although the objects can be placed on an HR diagram, their unknown distances remain a major limiting factor in deriving their physical parameters. Recent progress has made the study of the Yellow Hypergiants or post-Red Supergiants in depth as a sample a reality. In part this is due to better observations of the Magellanic Clouds (e.g. Spitzer SAGE) which allowed us to detect circumstellar matter at infrared wavelengths, while facilities such as the James Webb Telescope will allow us to go one step further and determine the dust properties and mass loss rates in great detail. A major step forward has been the progress in the detailed studies of massive Galactic clusters. Work published only over the last few years has more than doubled the number of known Galactic hypergiants (Clark et al. 2005, Figer et al. 2006, Davies et al. 2007a, see Figure 1), and prospects for the future are exciting, not only in terms of numbers of stars discovered as well as in-depth studies of individual cluster members.

Further and prolonged monitoring, both spectroscopically, and photopolarimetrically, of all objects, including the well-studied Galactic ones, will continue to bring up new insights into the evolutionary properties of the stars and the highest spatial resolution, interferometric observations, will provide invaluable information on the shaping of their nebulae.

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